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Benchmarking the energy efficiency of Dutch industry: an assessment of the expected effect on energy consumption and CO_2 emissions

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Abstract

As part of its energy and climate policy the Dutch government has reached an agreement with the Dutch energy-intensive industry that is explicitly based on industry's relative energy efficiency performance. The energy efficiency of the Dutch industry is benchmarked against that of comparable industries in countries worldwide. In the agreement, industry is required to belong to the top-of-the-world in terms of energy efficiency. In return, the government refrains from implementing additional climate policies.

This article assesses the potential effects of this agreement on energy consumption and CO_2 emissions by comparing the current level of energy efficiency of the Dutch industry—including electricity production—to that of the most efficient countries and regions. At the current structure achieving the regional best practice level for the selected energy-intensive industries would result in a $5 \pm 2\%$ lower current primary energy consumption than the actual level. Most of the savings are expected in the petrochemical industry and in electricity generation. Avoided CO_2 emissions would amount to 4 Mt CO_2. A first estimate of the effect of the benchmarking agreement in 2012 suggests primary energy savings of 50–130 PJ or 4–9 Mt CO_2 avoided compared to the estimated Business as Usual development (5–15%). This saving is smaller than what a continuation of the existing policies of Long-Term Agreements would probably deliver. © 2002 Published by Elsevier Science Ltd.

Keywords: Industry; Energy efficiency; Benchmarking

1. Introduction

Within industry, energy efficiency comparisons can be used as a tool to assess a company's performance relative to that of its competitors. For that purpose, the tool has been used for many years by the petrochemical industry and refineries, while the interest of other industries is growing. On a national level, policy makers can also use the tool to prioritise energy-saving options and to design policies to reduce greenhouse gas emissions. International comparisons of energy efficiency can provide a benchmark against which a country's performance can be measured to that of other countries. It can also aid in the evaluation of implemented policies.

In 1999, the Ministry of Economic Affairs of the Netherlands reached a voluntary agreement with the Dutch energy-intensive industry that is explicitly based on such a benchmarking. In this the so-called 'Benchmarking agreement', the energy-intensive industries are required to belong to the most efficient in the world. In return, the government agrees to refrain from introducing additional policies for the purpose of reducing energy consumption in these industries such as (specific national) energy taxation, emission ceilings or additional mandatory reduction targets (EZ, 1999).

When a government has to decide whether to abandon the option to implement more stringent energy or climate policies, it is important to know whether the proposed alternative (the Benchmarking agreement) will yield sufficient results in terms of primary energy savings and CO_2 emission reductions. The aim of this study is to provide an estimate of the magnitude of the avoided energy consumption and emissions that might result from the Benchmarking agreement. The following sectors are analysed: the iron and steel production, the chemical industry (distinguishing ammonia production and naphtha and gas–oil cracking), pulp and paper

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production and electricity production. In the Benchmarking agreement, the 'top-of-the-world' is defined as either the most efficient region worldwide or the best 10% of the plants analysed (the so-called decile approach). In the decile approach, the energy efficiency is required to at least equal the energy efficiency of the least efficient plant within the decile. For comparison, we also analyse the effects of a less stringent approach, based on the Top-3 of the most efficient regions and the best 25% of the plants analysed.

The assessment of the effect of the Benchmarking agreement is based on the difference between the current energy-efficiency levels in the Dutch energy-intensive industry and the level of efficiency attained in the currently (defined as 1995 ± 1 yr, depending on data availability) most efficient countries. As a result, the calculated energy savings and emission reductions represent an amount of energy and CO_2 emissions that would have been avoided in the hypothetical case that the Dutch industry currently would have been required to be among the most efficient in the world. This static approach is chosen because of two uncertainties in the future development. First, the Business as Usual (BaU) development of the energy efficiency of the Dutch industry is unknown and second, the future development of the energy efficiency of the industry in the countries the Netherlands is compared to is unknown. However, we will also give a first estimate of the expected influence of the Benchmarking agreement in 2012, compared to the expected BaU developments.

The methodology used in this study to estimate the energy efficiency of the industry in the Netherlands in comparison to that in other countries has been published in the 'Handbook on International Comparisons of Energy Efficiency in the Manufacturing Industry' (Phylipsen et al., 1998a). Wherever possible, plant data supplied by industry experts have been used after re-aggregation to a regional level. In other cases, national statistics and individual sector studies have been used with the assistance of national experts, gathered in INEDIS (the International Network on Energy Demand analysis in the Industrial Sector (INEDIS, 1999)), in the interpretation of energy consumption and industrial production data.

Section 2 describes the Benchmark agreement in more detail, while the methodology used to estimate differences in energy efficiency is explained in Section 3. Section 4 describes the industrial sectors included in the analysis and identifies important structural differences between countries. In Section 5, a cross-country comparison is made for the energy efficiency of each sector, and the potential emission reductions from the Benchmarking agreement are estimated. In Section 6, an indication is given of the effect of introducing a dynamic approach into our estimate of energy saving and emission reduction potentials. In Section 7, our results are compared with those of the alternative policies. In Section 8, our results are discussed. Finally, in Section 9, conclusions are drawn.

Energy consumption throughout this article is expressed through lower heating values.

2. The Benchmarking agreement

In July 1999, the Dutch government and several industrial trade organisations signed the 'Covenant Benchmarking Energy Efficiency'. On behalf of the government, the agreement was signed by the Minister of Economic Affairs, the Minister of Housing, Physical Planning and the Environment and the provincial authorities. Trade organisations that signed the agreement were the Netherlands Confederation of Industries and Employers (VNO–NCW) and those of the chemical industry (VNCI), the iron and steel industry (NIJSI), the non-ferrous metals industry (NFI), the petroleum industry (VNPI), the pulp and paper industry (VNP) and the electricity production sector (SEP). Individual companies can enter into the agreement after admission by the Benchmark Committee (EZ, 1999). In principle, all establishments with an annual energy consumption over 0.5 PJ are covered by the agreement.

Under the agreement, companies aim for their plants[3] to become (and remain) among the most efficient in the world as soon as possible, but no later than 2012 (measures are required to be implemented in phases. Implementation has to be as soon as possible, but no later than 2005, 2008 and 2012, based on the 'commercial viability', e.g. measures with an internal-rate-of-return of 15% have to be implemented no later than 2005). To this effect they have to determine the top-of-the-world in terms of energy efficiency once in every 4 years. The top-of-the-world is defined as the average efficiency of the most efficient region in the world or as the efficiency of the 10% of the most efficient plants worldwide (the decile approach) (EZ, 1999). In the decile approach, the energy efficiency is required to be at least equal to the energy efficiency of the least efficient plant within the decile. Companies that currently do not belong to the top-of-the-world have to submit a draft energy efficiency improvement plan, describing when, and with what measures, that efficiency level will be reached. After the plan is approved, the company is bound to the implementation of the measures described in it. Companies running more than one establishment can opt for a 'company benchmark', in

[3] In the agreement referred to as an 'installation', defined as the entire installation, required to produce or process a given product (as is also distinguished in environmental regulation). A company can also choose to benchmark an entire establishment or site (e.g. in the case of an integrated complex, consisting of both refineries and petrochemical plants).

which performance is not measured by establishment but for the company as a whole.

In return, the government will refrain from implementing 'additional specific national measures aiming to further reduce energy consumption or CO_2 emissions' (EZ, 1999). Note that this is phrased in such a way that e.g. European measures or national generic measures (such as a generic energy tax) are still allowed. Also measures focussing on the implementation of renewable energy or fuel switch are excluded from the agreement (i.e. can still be implemented by the government). In addition, energy-saving activities, that are not directed towards improving the energy efficiency of process installations (e.g. energy-efficient product design) are still possible (EZ, 1999).

Benchmarking will take place at a sub-sectoral level, so that only comparable processes are compared (e.g. the production of iron and steel or the production of ammonia). When the regional benchmark is used, regions are selected that are of a comparable production capacity as in the Netherlands. This could mean that countries are broken down into smaller regions or are clustered with other countries to form a region. The regions identified may vary by sector. In case, neither the regional nor the decile approach is feasible, a best practice approach can be chosen. In this approach, the world top is defined as being 10% less efficient than the most efficient plant worldwide.

3. Methodology

Comparing energy efficiency between countries is not straightforward because of differences in economic structure. Also within a country, the economic structure can change over time. At a sectoral level, we define sector structure as the product mix (e.g. printing paper vs. sanitary paper) within a sector, including differences in product quality (e.g. virgin paper vs. secondary paper). Feedstock and process type are not considered to be indicators of sector structure, unless they influence the product mix (or product quality) (Phylipsen et al., 1998a). Also factors that are not amenable for modification by industry (like local availability of feedstocks) are considered to comprise structural differences between countries.

Due to the influence of sector structure on energy intensity, cross-country or cross-time comparisons cannot be made based solely on trends in the absolute value of indicators such as the specific energy consumption (SEC, energy consumption per tonne of product) for each country. In our methodology, we, therefore, compare the actual SEC with a reference SEC that is based on the given sector structure. This means that both the actual SEC and the reference SEC are similarly affected by changes in sector structure. Here, the reference SEC is defined as the SEC of the best commercially operating plant observed worldwide (also referred to as 'best plant')[4]. Such a best plant is defined for each process and the sectoral value is calculated as the weighted average, based on the shares of the various processes and products according to Eq. (1). The difference between the actual and reference SEC is used as a measure of energy efficiency, because it shows which energy efficiency level would be achieved in a country with a particular sector structure in case only best plant technologies would be used. The smaller the difference, the better the energy efficiency is. The relative differences between actual and reference SEC can be compared between countries. Usually this is done by calculating an energy efficiency index (EEI): the ratio between actual SEC and reference SEC. If only best plant technology is used within a sector, the EEI would equal 100. An EEI of 105 means that the SEC on average is 5% higher than the reference level, so that 5% of energy could by saved at the given sector structure by implementing the reference level technology.

$$\begin{aligned}\mathrm{EEI_a} &= 100\frac{\mathrm{SEC_a}}{\mathrm{SEC_{ref,a}}}\\ &= 100\frac{\sum_i E_i/\sum_i m_i}{\left(\sum_i m_i\,\mathrm{SEC}_{\mathrm{ref},i}\right)/\sum_i m_i}\\ &= \frac{E_\mathrm{a}}{\sum_i m_i\,\mathrm{SEC}_{\mathrm{ref},i}}.\end{aligned} \tag{1}$$

In which $\mathrm{EEI_a}$ is the energy efficiency index for sector a, $\mathrm{SEC_a}$ the specific energy consumption for sector a, $\mathrm{SEC_{ref,a}}$ the reference specific energy consumption for sector a, E_i the energy consumption for product i, m_i the production quantity of product i, SEC_i the specific energy consumption of product i, $\mathrm{SEC}_{\mathrm{ref},i}$ a reference specific energy consumption of product i, E_a the energy consumption in sector a, and i the products 1–n made in sector a.

Furthermore, it may be that changing sector structure can also lead to a decrease in CO_2 emissions in case changes result in a less energy-intensive structure (e.g. in the case of the pulp and paper industry increasing the

[4] The work on International comparisons of energy efficiency in industry started in 1993. Before that, studies on national energy efficiency improvement potentials involved the analysis of energy consumption and implemented technologies at foreign plants. Hence, the development of best plant technology has been monitored during a long-time period. The selection of the best plant (see e.g. Table 1) is based on an extensive survey of literature and exchange of information within the network during those years. Especially countries that are generally considered to be among the most efficient, such as Japan, South Korea, Germany and the Netherlands have been thoroughly analysed. It cannot be guaranteed, however, that there is no single plant with a lower SEC than the ones listed here. The difference with the best plant as identified in our analysis, however, is not expected to be large, because generally the industries considered are mature industries, in which technological development (for energy efficiency purposes) occurs in small, incremental steps.

share of secondary paper production). However, in this analysis we focus on energy efficiency as a way to decrease emissions, since sectoral change is not a part of the Benchmarking agreement.

4. Sector description and structure identification

4.1. The iron and steel industry

In the iron and steel industry, iron making and steel making are the main processes. Iron is produced by reducing iron ore with coke (or coal) in the blast furnace (to produce pig iron) or by direct reduction (to produce directly reduced iron, or DRI). The pig iron serves as input for the basic oxygen furnaces (BOF) or open hearth furnaces (OHF), in which it is converted into crude steel. The pig iron can also be sold as cast iron. Secondary steel is produced in the electric arc furnace (EAF), using mainly scrap. The EAF can also be fed with DRI to enhance steel quality or in case if high-quality scrap is scarce or expensive.

In the iron and steel industry product mix, defined as the share of iron, slabs, hot-rolled steel and cold-rolled steel is an important structural indicator. Furthermore, feedstock (iron ore vs. scrap, used to produce primary and secondary steel, respectively) is considered to be a structural indicator, because scrap input can influence product quality (i.e. product mix) due to contaminations from other metals. Also, the amount of scrap available to a steel plant may be a limiting factor (i.e. not amenable by the steel producer) in choosing between iron and scrap. The SEC should, therefore, be expressed as a function of scrap input (or the share of EAF steel as an approximation) and product mix (Phylipsen et al., 1998a). The reference SECs used in the analysis are shown in Table 1.

Table 1
Reference SECs for various steps in the production process of iron and steel. The SECs exclude coke making (in the integrated route) and anode making (in the EAF route). The primary energy has been calculated taking into account a 40% conversion efficiency for electricity generation

Process	Fuel use (GJ/t)	Electricity use (GJ_e/t)	Primary energy use (GJ/t)
Blast furnace[a]	14.89	0.23	15.47
Direct reduction[b]	10.03	0.36	10.93
BOF-slab[c]	−0.57	0.11	−0.30
EAF-slab[d]	0.94	1.10	3.72
Hot rolling[e]	1.53	0.35	2.41
Cold rolling[e]	1.10	0.53	2.43

[a] The 'benchmark SEC' represents the 1994 performance at Hoogovens, the Netherlands (50% pellet feed, 50% sinter feed, and blast furnace) and is based on their 1988 performance (Worrell et al., 1993) and the estimated effect of measures implemented in the period until 1994 under the Long Term Agreement, based on Farla et al. (1998).

[b] Based on actual operations data for gas-based Midrex DRI plants with pellet and/or lump ore feed (Midrex, 1999).

[c] Assuming the 1988 performance at Hoogovens and 100% continuous casting, and implemented measures (see footnote a).

[d] Assuming a Fuchs finger shaft EAF with scrap preheating and oxygen/fuel injection, based on performance at Von Roll, Switzerland (Jones, 1997).

[e] Assuming the 1988 performance at Hoogovens of a hot strip mill and cold strip mill, and implemented measures (see footnote a).

4.2. Ethylene production

Ethylene is produced by steam cracking of hydrocarbon feedstocks. In the presence of steam, hydrocarbons are cracked into a mixture of shorter, unsaturated compounds. A series of separation steps produces fractions consisting of ethylene, propylene, a C_4 fraction (amongst others butadienes) and pyrolysis gasoline. Feedstocks used are ethane, LPG, naphtha, gas oils and, sometimes, coal-derived feedstocks. Most of the installations used today can handle different types of feedstock (Chemfacts, 1991).

The specific energy consumption of cracking is influenced by feedstocks and by processing conditions (temperature, pressure, furnace residence time), referred to as severity. Because also product mix is determined by these parameters, both feedstock and severity have to be taken into account when comparing different countries. For the comparison of individual crackers, a benchmarking system has been developed by Solomon Associates Inc. Solomon set up an extensive network within the petrochemical industry. Participating companies provide Solomon with very detailed data on production, throughput, energy consumption, installed technology, etc. on a bi-annual basis. In return, Solomon offers companies, a comparison of their own plant's performance with that of all the other participating plants (anonymously). Plant performance is measured by comparing the plant's actual energy consumption to a reference level of energy consumption, based on the most efficient technology available as calculated by the Pyrolysis Yield Prediction System (PYPS); a model developed by petrochemical technology licensor ABB Lummus Crest. The reference technology is based on an ABB Lummus Crest SRT-5 coil, a furnace coil outlet pressure of 25 psia (170 kPa), essentially complete ethylene and propylene recovery and no gas turbine integration (Solomon, 1995). Specific energy consumption is defined as the net energy consumption per unit of high-value chemicals (including hydrogen, ethylene, propylene, a mixed butadienes fraction and a BTX fraction). The analysis accounts for differences in severity, in feedstocks used in the cracker and in supplemental feeds (feeds that bypass the cracking furnace). In the present analysis, only naphtha and gas oil crackers are included, since the Netherlands' companies only crack liquid feedstocks.

4.3. Ammonia production

The most important step in producing ammonia (NH_3) is the production of hydrogen, which is followed by the reaction of hydrogen and nitrogen to ammonia. Hydrogen can be produced by steam reforming of natural gas or by partial oxidation of oil residues. Partial oxidation usually requires more energy than steam reforming (up to 30–40% more (Worrell and Blok, 1994)), but has the advantage of a high feedstock flexibility.

Since the products of both processes are identical, no structural indicators need to be taken into account in ammonia production[5]. This means a straightforward comparison can be made of the specific energy consumption, expressed in GJ/t ammonia. Therefore, also no reference SEC is needed to calculate an EEI (for comparison: the most efficient plant in our analysis has a SEC of about 29 GJ/t NH_3).

4.4. The pulp and paper industry

In pulp and paper production, pulping and paper-making are the most important steps. In pulping, wood fibres are separated from each other mechanically or chemically. Mechanical pulping leaves the lignin (acting as a binder between wood fibres) in the pulp, which results in a lower fibre quality over time because of lignin degradation. This limits the use of mechanical pulping mainly to news printing paper. Chemical pulping results in higher quality paper, but with a lower yield (because the lignin is dissolved). In paper production, the feedstock mixture is dispersed in water and refined (fibres are processed into the desired length). Besides pulp, also waste paper can be used as a feedstock, although paper quality is influenced by the relative amount of waste paper used (Worrell et al., 1994).

In pulp and paper production product mix (the relative shares of different paper types) is a structural indicator. We distinguish news printing paper, (high-quality) printing paper, wrapping paper (packaging), sanitary paper and others (including board). The type of pulping process used partly determines product type and is, therefore, also considered a structural aspect. Because of import and export streams of pulp, product mix and process mix are not necessarily the same. Therefore, both product and process type have to be taken into account. For reasons of product quality and feedstock availability, the relative shares of waste paper and pulp used, is also considered to be a structural indicator. The reference SECs used in the analysis are shown in Table 2. Note that these reference values do not satisfy the strict definition of 'best plant' as used for some of the other sectors, as such data could not be derived for this study. The values in the table should be considered as 'typical values for a modern plant'.

Table 2
Reference SEC for pulp and paper production (Farla et al., 1997)

Product	Fuel/heat (GJ/t)	Electricity (GJ_e/t)	Primary (GJ/t)
Mechanical wood pulp	−2.1	5.3	11.2
Chemical wood pulp	10.0	2.5	16.3
Other wood pulp	−3.0	6.0	12.0
Other fibre pulp	−3.0	6.0	12.0
Recycled fibre input	0.4	1.4	3.9
Newsprint	2.5	1.4	6.0
Printing/writing paper	7.0	2.0	12.0
Sanitary paper	5.0	2.4	11.0
Packaging paper	5.0	1.5	8.8
Other paper	6.0	1.8	10.5

4.5. Public electricity production

In the Netherlands, electricity production is mainly based on coal and natural gas. Therefore, in this paper, we will compare these types of electricity production with the same type in other countries.

The steam cycle is still the dominant process in fossil fuel-based electricity generation. Fuel is combusted in a boiler where high-pressure/high-temperature steam is raised, which is expanded through a steam turbine. Often a steam-reheating step is included to increase overall efficiency of the plant. The steam cycle is suited for all kind of fuels. The most prominent alternative for the steam cycle is the combined cycle, consisting of a gas turbine and a steam turbine. In this case, the fuel is fed to a gas turbine that produces both electricity and high-temperature off-gases. The off-gases are fed to a waste heat boiler, where high-pressure steam is raised, which is subsequently expanded in a steam turbine. A combined cycle plant is generally fired with natural gas. There are several alternative schemes, especially for coal-based power generation, like integrated coal gasification combined cycle plants and fluidised bed combustion plants, but none of these have a relevant share in power production yet.

One could argue that the product of coal-based and gas-based electricity production is the same, and that fuel type in electricity production should, therefore, not be considered a structural indicator. However, the

[5] Geographical availability of natural gas could be considered as a structural indicator. However, natural gas infrastructure is rapidly increasing. Furthermore, 80% of ammonia is already produced by steam reforming of natural gas.

choice for fuel diversification has in the past often been made at the government level for strategic purposes, e.g. fuel diversification and the use of indigenous resources or employment. The choice for a particular type of fuel was, therefore, outside the realm of the industry and is considered to be a structural indicator. Therefore, power plants using both types of fuel are dealt with separately in this article. Another structural difference that can exist between countries is the occurrence of heat extraction, either for industrial purposes or for district heating. Heat extraction causes the electricity generating efficiency to decrease, although the overall efficiency for heat and electricity together is higher than when the two are generated separately. Therefore, a correction for heat extraction is applied, according to Eq. (2), in countries where this is relevant, after which the corrected efficiencies can simply be compared. The efficiency of the most efficient plants operational is 55% for gas-fired plants (the Eems plant in the Netherlands and 45% for coal-fired plants (plant in Denmark).

$$\eta = \frac{E + sH}{F}. \tag{2}$$

In which η is the (gross) electricity conversion efficiency (%), E the total (gross) amount of electricity produced, H the total amount of heat produced, F the total amount of fuel used, and s the substitution factor between heat and electricity, indicating the amount of electricity production lost per unit of heat extracted from an electricity plant.

For district heating systems the substitution factors vary between 0.15 and 0.20 (Phylipsen et al., 1998a). In our analysis we have used a value of 0.175. It must be noted that if heat is delivered at higher temperatures (e.g. to industrial processes) the substitution factor can be higher. However, in the time period considered heat delivery by public power plants to industry was negligible.

5. Effect of benchmarking on energy use and co$_2$ emissions

In this section we describe the actual, static benchmarking analysis. First of all we select the countries to be included in our analysis. By sector we compare the energy efficiency of the Dutch industry to that in the other countries. Based on the difference between the Dutch efficiency and that of the most efficient country or, when the data allow, region in the world we calculate the energy savings and emission reductions. In case sufficient data are available we also give the estimated savings for the decile approach.

5.1. The iron and steel industry

On the basis of previous work, data are available for a number of countries. Worrell et al. (1994) give data for 10 EU countries for 1988. Worrell et al. (1997a) provide more recent data for six countries worldwide. Phylipsen et al. (1999) provide time series for six, mostly developing, countries up to 1995/1996. Phylipsen et al. (1998b) show data for two other countries. Due to partial overlap, this results in a set of 18 countries, for various periods in time. Although some of the data are fairly old, one gets a good overview of the relative differences between the countries.

Fig. 1 shows the energy efficiency index for the iron and steel industry for the various countries. The figure shows that the iron and steel industry in the Netherlands is relatively efficient, together with that in Brazil, Germany, Japan and South Korea. Countries like

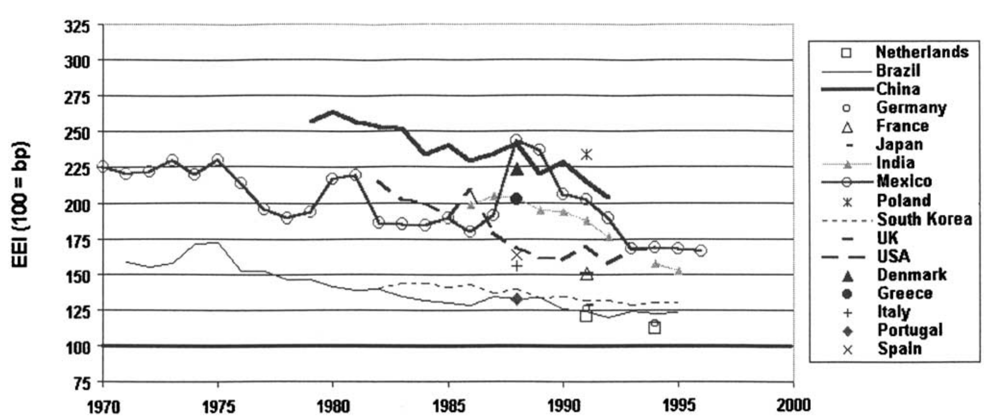

Fig. 1. A comparison of the energy efficiency index in iron and steel production in various countries. Data for Brazil, China, India, Mexico and the US are from (Phylipsen, 2000), for Germany, France, and Japan from (Phylipsen et al., 1998b), for Poland from (Worrell et al., 1997a) for the UK from (Groenenberg et al., 1999), for others from (Worrell et al., 1994). Note that the data for India are for integrated steel plants only. Time series for electric plants are not available. The average energy efficiency index for steel production (including electric steel) is estimated to be 152 for 1994–1995 (Phylipsen, 2000).

Poland, India, China and the United States are relatively less efficient. The most recent data show the Netherlands to be slightly more efficient than Germany. The other efficient countries have a slightly higher efficiency index. Benchmarking is, therefore, not expected to result in any energy savings or CO_2 emission reductions in the top-1 benchmark.

The present analysis is based on about 72% of world capacity (IISI, 1999). For the excluded countries energy-efficiency indicators could not be calculated. However, on the basis of primary energy intensity data some conclusions can be drawn about the energy efficiency of the iron and steel industry in these countries. For a number of countries primary energy intensities are so high, that differences in product mix alone cannot account for the difference with the Netherlands. A country with the most energy-intensive structure possible (100% primary steel, 100% cold-rolled steel) would have a primary energy intensity of about 21 GJ/t. All countries whose primary energy intensity is above 21 GJ/t will, therefore, be less efficient than the Netherlands. The same is true for countries whose primary intensity is about 21 GJ/t, but that do have EAF-based steel production. Based on this reasoning the following countries are also estimated to be less efficient than the Netherlands: South Africa (Phylipsen et al., 1999), Taiwan (Lefevre et al., 1995; APERC, 1999), Canada, Australia (both (APERC, 1999)), Finland (VTT, 1997), Turkey (Tasdemiroglu, 1993; IEA, 1997a, b), Indonesia, the Philippines, Chile (all (APERC, 1999)), the Czech Republic (Nieuwenhout et al., 1994a) and the Slovak Republic (Nieuwenhout et al., 1994b). We further assume that countries from Eastern Europe and the former Soviet Union are less energy efficient than the Netherlands. This assumption is consistent with the results for Poland and the Czech and Slovak Republics and the share of OHF-based production still existing in countries in Eastern Europe and the former Soviet Union. This increases the total coverage to 95%. We, therefore, do not expect the conclusions to be significantly affected by countries that are currently not included in our analysis.

5.2. Ethylene production

For this study Solomon provided data for the major countries that use liquid feedstocks, grouped into regions with a comparable production capacity as the Netherlands. This includes all the European producers, Japan, Korea, the US and countries in South America. Fig. 2 shows a comparison of the energy efficiency in liquid cracking based on the Solomon methodology. On a regional basis, the average energy efficiency index of the Dutch crackers is slightly above the average of the whole study. Four of the areas included in this analysis are more efficient than the average of the Dutch crackers: the Mediterranean area, the Rhine river area in Northwest Germany, the area of Japan, Korea and South America.

Fig. 3 shows the distribution of the energy efficiency index of individual plants included in the Solomon analysis. With a benchmark requiring the Dutch crackers to be as efficient as the most efficient region (Japan and South Korea) the Dutch energy-efficiency index would have to equal 117, corresponding to a specific energy consumption of 13.1 GJ/t of high-value chemicals. With a total production of high-value chemicals of 5.2 Mt, this would save 18 PJ in primary energy consumption. The exact breakdown into different fuels used in cracking is not known; as an approximation we assume that predominantly liquid fuels are used with a CO_2 emission factor of 73 kg CO_2/GJ (IPCC, 1996). Avoided CO_2 emissions can then be calculated to be 1.3 Mt CO_2.

On a percentile basis, the average energy efficiency of the Dutch crackers is equal to the average energy

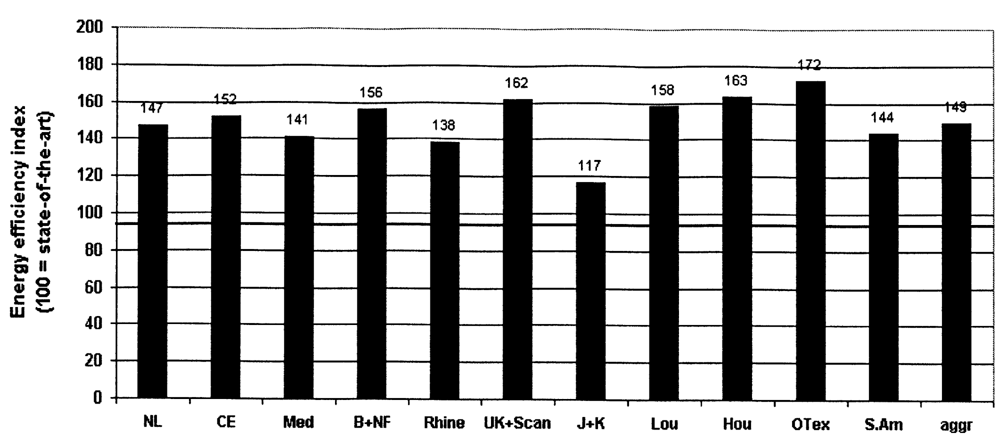

Fig. 2. A comparison of the energy efficiency index in liquid-based ethylene production for a number of regions in 1995 according to the Solomon methodology. An efficiency index of 100 represents the state-of-the-art technology (Phylipsen et al., 1998b).

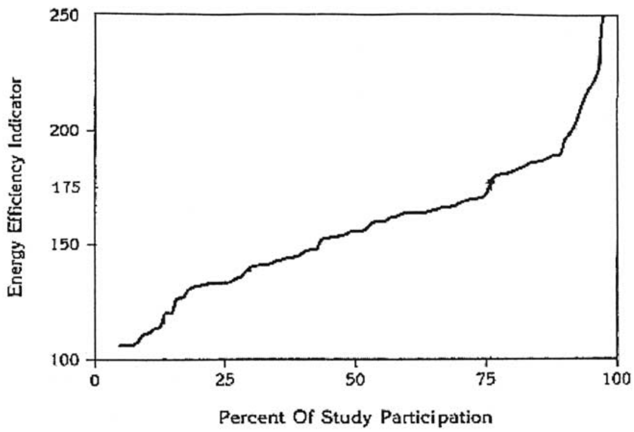

Fig. 3. Distribution of the energy-efficiency index of all petrochemical plants included in the Solomon analysis (Phylipsen et al., 1998b).

efficiency of the second quartile of the plants included in the Solomon survey. In case 'top-of-the-world' is defined as the best 10% of plants the average energy efficiency index of the Dutch crackers would have to be below 110 (and the specific energy consumption below 12.2 GJ/t of high-value chemicals). Resulting energy savings would be 21 PJ. Avoided CO_2 emissions in this case amount to 1.6 Mt.

Worldwide ethylene production amounted to 70 Mt in 1995 (Weirauch, 1996). About 59% of ethylene capacity is liquids based (Manning, 1997), corresponding with a global ethylene production of 41 Mt out of liquid feedstocks. The present analysis is based on 33 Mt of ethylene from liquid cracking or 80% of world capacity. The major part of the missing 20% is produced in countries such as the former Soviet Union (5%), China (5%), India (2%) and Eastern European countries (4.5%) (see e.g. Gielen et al., 1996). These countries are not expected to be more efficient than the area of Japan and Korea. This leaves only a few, currently small-capacity countries in Asia that might be more efficient because of rapidly growing economies such as Thailand and Malaysia. The ethylene production in these countries, however, is very low, 0.3 Mt/yr for Malaysia and about 0.6 Mt/yr for Thailand (Weirauch, 1996). These, even together, comprise too small regions to be compared to the Netherlands and clustering them to regions of comparable size decreases the chance the average efficiency is better than that of the Netherlands. We, therefore, do not expect the conclusions to be affected by countries that are currently not included in our analysis.

5.3. Ammonia production

For this study data on the energy efficiency in ammonia production have been supplied by Plant Surveys Inc. (PSI, 1998). Countries included in the analysis are from Europe and Oceania (coverage about 85%), North America and Latin America (coverage about 65%). Excluded regions are Eastern Europe, the former Soviet Union, Africa and parts of Asia and Latin America[6]. Fig. 4 shows the specific energy consumption in various regions in ammonia production (Phylipsen et al, 1998b). Since no structural differences have to be taken into account in ammonia production, SEC can here be used as a measure of energy efficiency. As shown in Fig. 4 of the regions included in the present analysis only Canada is more efficient than the Netherlands.

Fig. 5 shows that the Netherlands *average* energy efficiency of ammonia production belongs to the first quartile of most efficient plants included in the present analysis. If the Dutch ammonia industry is required to be as efficient as the industry in the most efficient region (Canada) the average primary energy consumption has to be reduced from 34.0 to 32.6 GJ/t ammonia. Total primary energy savings are estimated at 5 PJ and avoided CO_2 emissions at 0.3 Mt. For a benchmark of the best 10%, the estimates are the same. It must be noted that differences among individual plants within the Netherlands are large (with the most efficient plant having a SEC of about 25% lower than the least efficient plant) (PSI, 1998).

The present analysis is based on about 52% of world capacity. A large part of the excluded regions is not expected to be more efficient than the Netherlands, such as China, Eastern Europe and the former Soviet Union. Ammonia production in these regions accounts for 45% of world capacity (PSI, 1998). Other parts, however, may include more efficient regions, e.g. in Asia. Countries that could possibly be relatively efficient because of rapid development (Thailand, Taiwan, Malaysia, Singapore, etc.) are still very small producers. Capacities are $<10\%$ of Dutch capacity. Therefore, national average SEC is not expected to be much lower than that of Canada.

5.4. Pulp and paper industry

On the basis of previous studies, data for a number of countries are available. Worrell et al. (1994) give data for 1988 for the European Union (12 member states at that time). Farla et al. (1997) and Worrell et al. (1997b) give data for 8 and 9 countries worldwide. Ewing (1985) gives older data for some developing countries. In total for 16 countries data are available for various periods of time. The energy efficiency indices of these countries are shown in Fig. 6. To keep the figure clear, the energy efficiency indices for less efficient countries are not shown.

[6] Excluded in Asia: China, Iran, Iraq, North Korea; excluded from Latin America: Mexico, Cuba.

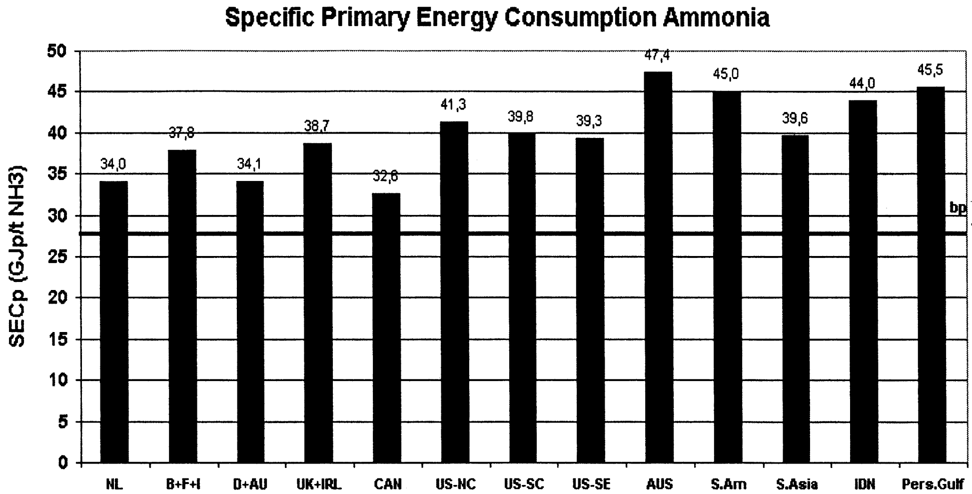

Fig. 4. A comparison of the energy efficiency (expressed as SEC) of ammonia plants in various regions (PSI, 1998; Phylipsen et al., 1998b). The comparison is based on the lowest SEC obtained during a number of days in a row (30 days) in the period 1994–1996. The horizontal line marked 'bp' represents the lowest SEC observed among the plants included in the analysis. The energy consumption is on a lower-heating-value basis.

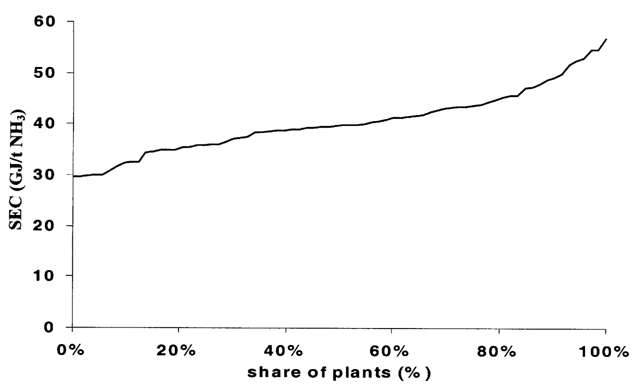

Fig. 5. Distribution of the SEC of all ammonia plants included in the PSI analysis (Phylipsen et al., 1998b). The energy consumption is on a lower-heating-value basis.

From the data compiled up to now we see that, regarding energy efficiency in the pulp and paper industry, the Netherlands belong to a top group, that further includes Finland, France, Germany, Japan and South Korea. Within this top group the uncertainties in the figures cause difficulties in establishing the exact order. Uncertainties can be caused by different ways combined generation of heat and power (CHP) is dealt with in statistics or differences in system boundaries regarding the energy consumption in the paper and board converting industries. If the energy-conservation effect of CHP is allocated to the pulp and paper industry and if energy consumption figures are cleaned up for energy consumption in the paper and board converting industries, the Netherlands and Germany appear to be among the most efficient. Based on this ranking we do not expect benchmarking to result in a significant energy savings or emission reductions. These conclusions, however, have a preliminary character. The uncertainty margins in the figures for the pulp and paper industry may be larger than for the other sectors, mainly because of the issues related to CHP that can be represented in statistics in different ways.

The present analysis is based on about 74% of world capacity. As we have done for steel production also for paper production some conclusions can be drawn on the basis of primary energy consumption data. The most energy-intensive structure possible in the paper industry would be based on a pulp to paper ratio of one (assuming no significant net export of pulp occurs). With an efficiency comparable to the Netherlands (EEI = 112) this would roughly correspond to a primary energy intensity of 27.5 GJ/t. On the basis of primary energy intensity data we can conclude the following countries (not included in Fig. 7) are also less efficient than the Netherlands: Norway (VTT, 1997), New Zealand (EECA, 1997), Austria, (IEA, 1997a, b), China, the Philippines (all (APERC, 1999)), India (WEC, 1995), Brazil (de Oliveira, 1996), Colombia, Turkey, Pakistan (all (Ewing, 1985)), the Czech Republic (Nieuwenhout et al., 1994a) and the Slovak Republic (Nieuwenhout et al., 1994b). This increases coverage from 74% to 91%. If we further assume other countries from the Eastern Europe and the former Soviet Union to be less efficient too, the coverage increases to 95%. This assumption is confirmed by Grün (1999) for Poland, Hungary, Romania and, again, the Czech and Slovak Republics. Thailand and Taiwan are larger producers, but unfortunately no conclusions can be drawn on their efficiency. For Taiwan, primary intensity is substantially higher than that of the Netherlands (APERC, 1999), but no data is available on the pulp to paper ratio. Data provided on the primary intensity for

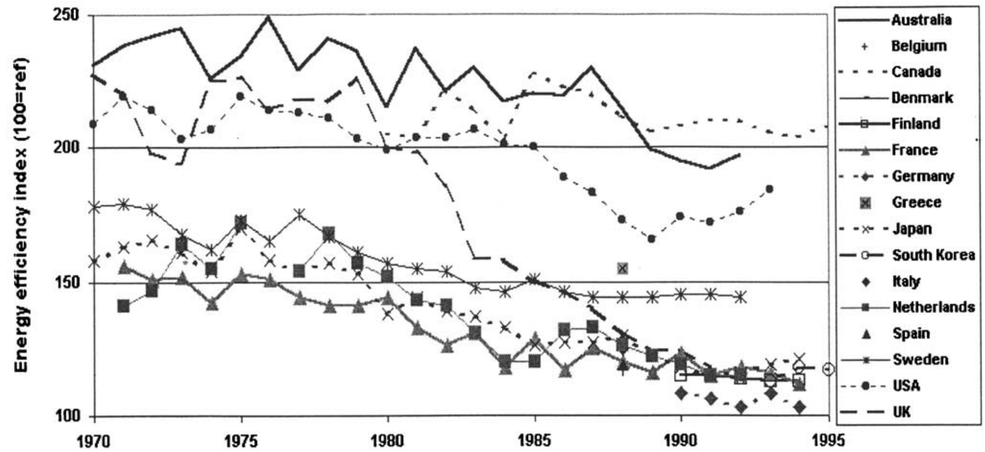

Fig. 6. A comparison of the energy efficiency index for pulp and paper production in various countries. Data for Australia, Japan, the Netherlands, the UK, the US and Sweden are from (Farla et al., 1997), for South Korea from (Park, 1997), for Germany from (DIW, 1997), for Canada from (de Jong, 1998), and for Belgium, Denmark, Greece and Italy from (Worrell et al., 1994).

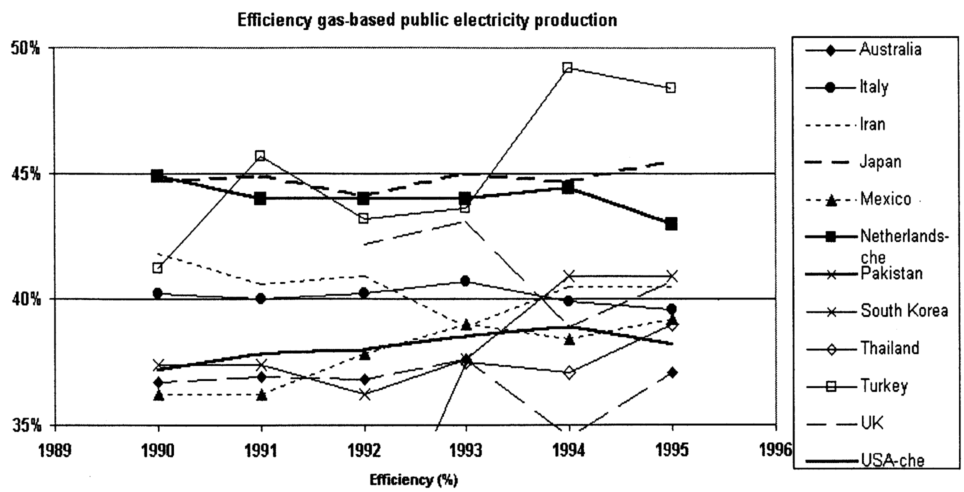

Fig. 7. The efficiency of gas-based public electricity generation (IEA, 1997a; IEA, 1997b). Only countries with an efficiency above 35% are shown. A country is marked 'che' in case substantial heat extraction occurs (e.g. from public CHP plants); the electricity generation efficiency is corrected for that.

Thailand are significantly below the best plant energy consumption (APERC, 1999). A possible explanation is that waste energy is not included in the Thai data, but further investigation is needed to clarify this point.

For the time being, we do not expect either of these countries to be that much more efficient than the Netherlands and Germany that our conclusions are significantly affected.

5.5. Public electricity generation

Data for fuel input, electricity output and—in case of (public) CHP plants—heat output are taken from IEA Energy Balances (IEA, 1997a, b) for countries with an electricity production in 1995 of more than 10 TWh. This results in a selection of 24 countries for gas-based electricity production and 24 countries for coal-based generation. In Figs. 7 and 8 average gross[7] efficiencies of natural gas-fired power plants and coal-fired power plants for the period 1990–1995 are presented. In cases where heat is produced, the efficiency corrected for heat extraction (noted with 'che') is given. For countries for which the data were apparently unreliable (strong fluctuations from year to year, extremely high or low efficiencies) results have been omitted. Most of these countries are in the former Soviet Union or oil- and gas-producing countries. In the first case, the unreliable results may be due to inadequate statistics. In the second case, an important cause of errors is that fuel that is

[7] Gross means that the own energy consumption of the power plant is not taken into account when determining the conversion efficiency. It does not refer to the use of higher heating value (all quantities in this paper are on a lower-heating-value basis).

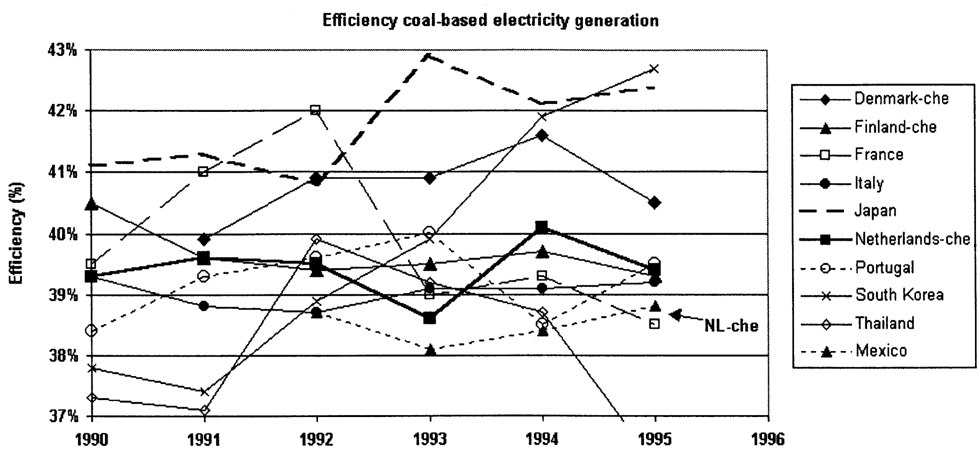

Fig. 8. The efficiency of coal-based public electricity generation (IEA, 1997a; IEA, 1997b). Only countries with an efficiency above 38% are shown. A country is marked 'che' in case substantial heat extraction occurs (e.g. from public CHP plants); the electricity generation efficiency is corrected for that.

Table 3
Estimate of average power plant efficiencies (in %) in selected countries

Country	Gas-based capacity	Country	Coal-based capacity
Japan	43–45	Denmark	41–42
The Netherlands	42 (up to 1995)	Finland	39–40
	47.5 (in 1996)	Japan	41–43
South Korea	~41	The Netherlands	39–40
Turkey	48–49	South Korea	38
UK	~44		

produced on site is not accounted for as input to the power plants.

On the basis of these figures we find that the highest efficiencies for natural gas-fired power generation can be found in Japan, the Netherlands, Turkey, the United Kingdom and South Korea. For coal-based generation, high energy conversion efficiencies can be found in Denmark, Finland, Japan, the Netherlands and South Korea. For these countries we have compared IEA data with data from national sources, such as national statistics and utility information. For Denmark, Finland and Turkey, the results from the national sources (ENS, 1998; Hofman, 1998; Lehtila, 1998; Gada, 1998) are consistent with IEA data. For Japan and South Korea national sources list lower efficiencies than we calculated on the basis of IEA data (for Japan: (ECC, 1997; Tepco, 1997; JEPIC, 1998), for South Korea (Kepco, 1998)). The UK national data give rise to higher efficiencies than calculated on the basis of IEA data (Wilson, 1998). Differences can be explained by incomplete coverage of all the power companies and an incorrect distinction between public and non-public electricity generation. Table 3 shows the estimated electricity generation efficiencies, corrected for the above discrepancies. The range in efficiencies represents the uncertainties in the estimates.

It can be concluded that for gas-based power generation only Turkey is more efficient than the Netherlands[8]. For coal-based power plants Japan and Denmark are more efficient than the Netherlands. In case the Top-1 region requirement is applied, energy savings are estimated to be 21–27 PJ or 1.8–2.3 Mt CO_2.

The present analysis is based on about 94% of world capacity for coal-based generation and 85% for gas-based capacity. The excluded regions have an electricity production <10 TWh per fuel type, which is much smaller than in the Netherlands (29 TWh coal-based and 35 TWh gas-based generation (IEA, 1997a)). Clustering different countries to a region of comparable size to the Netherlands decreases the chance of their average efficiency to be higher than that of the Dutch power sector. Furthermore, countries that might be expected to have high efficiencies because of a high growth rate (such as South Korea, Taiwan, Thailand and Malaysia) are already included in the analysis. A preliminary estimate of excluded high-growth countries, such as Hong Kong, Indonesia, the Philippines, Singapore and Vietnam shows countries to be less efficient than the

[8] Note that this is the case when the efficiency of the Dutch electricity production in 1996 is compared to the efficiency of other countries in 1995. In 1995, the Dutch gas-based efficiency was also lower than that of Japan and the UK. By then, no 1996 data were available for the other countries, but improvements are expected to be substantially smaller than in the Netherlands. The UK and Japan have a substantially larger generating capacity, so the addition of one plant will have a smaller impact on overall efficiency than in the Netherlands. Furthermore, expansions of the size that occurred in the Netherlands (1700 MW) do not occur that often.

Table 4
Estimated energy savings expected to result in case the Dutch industry is required to belong to the most efficient in the world in a static benchmark. Results are shown for various definitions of the 'Top-of-the-world'

Sector	Energy savings (PJ)			
	Top-1	Top-3	Top 10%	Top 25%
Iron and steel	0	0		
Ammonia	5	0	5	0
Ethylene	18	4.0	~21	7.1
Pulp and paper	—[a]	0		
Power generation[b]	21–27	0		
Total	43–49	4		

[a] For the pulp and paper industry uncertainties were too large to determine the distance to the Top-1 benchmark. The estimated energy savings will, however, be no larger than 1 PJ.
[b] Based on 1996 efficiency figures for the Netherlands.

Table 5
Estimated avoided CO_2 emissions expected to result in case the Netherlands is required to belong to the most efficient in the world in a static benchmark. Results are shown for various definitions of the 'Top-of-the-world'

Sector	Avoided emissions (Mt CO_2)			
	Top-1	Top-3	Top 10%	Top 25%
Iron and steel	0	0		
Ammonia	0.3	0	0.3	0
Ethylene	1.3	0.3	~1.6	0.5
Pulp and paper	—	0		
Power generation[a]	1.8–2.3	0		
Total	3.4–3.9	0.3		

[a] Based on 1996 efficiency figures for the Netherlands.

Netherlands (IEA, 1998). Therefore, the incomplete coverage is not expected to significantly affect our results.

5.6. *Overall results*

The results of the static benchmark are summarised in Tables 4 and 5. Table 4 shows energy savings that are estimated to result from a static benchmark, while Table 5 shows the avoided CO_2 emissions. For petrochemicals and ammonia also a percentile benchmark requirement could be calculated and the results of applying such a benchmark are also shown. Since total energy consumption of the sectors analysed amounts to 830 PJ of fuel and 40 PJ of final electricity, the more stringent benchmark leads to a 5% energy saving compared to the sectors' total energy consumption (de Beer et al., 1994). Most of the savings will be found in the petrochemical sector and the electricity sector.

6. Estimate of the future effect of benchmarking

The previously reported potential energy savings and emission reductions are based on a static approach to benchmarking: how much emissions would have been avoided, if the Netherlands' industry would at this moment have to belong to the top of the world in terms of energy efficiency. In this section, a preliminary estimate is given of the effect of the Benchmarking agreement taking into account expected developments in production and energy efficiency in the Netherlands and abroad until 2012 (based on de Beer and Blok (1999)).

In order to estimate the expected energy consumption and CO_2 emission levels in 2012 in the Netherlands and the effect of the Benchmarking agreement, information is needed on the expected production growth in the Netherlands (in physical terms) and the expected autonomous energy efficiency improvement rates in the Netherlands and abroad.

The expected production of basic materials in the Netherlands is assessed sector by sector on the basis of investment plans of companies and sector organisations and sector analyses.[9]

For the development of energy efficiency in the Netherlands and abroad a Business as Usual (BaU) scenario is developed. In the BaU scenario, total energy consumption develops as a function of the growth in production and autonomous efficiency improvements, estimated by sector. The autonomous trends in efficiency improvements depend on expectations of newly built capacity, current efficiency and investment plans and economic prospects of companies and countries (de Beer and Blok, 1999). Table 6 presents an overview of the assumptions for various sectors and the estimated energy savings and emission reductions resulting from the dynamic benchmark.

Expected energy savings are calculated by comparing the energy consumption resulting from introducing the benchmark to total energy consumption in the BaU scenario and the frozen efficiency. To determine the numerical value of the dynamic benchmark two cases are used. In the first case, the currently most efficient region (as identified in the previous sections) remains the most efficient region, whose efficiency develops according to the BaU scenario. In the other case, the possibility of the emergence of a new 'most efficient region' is assessed.

Based on the assumptions listed in Table 6 the energy savings resulting from a benchmark agreement can be estimated at 48–130 PJ in 2012 compared to the Business as Usual development. This represents

[9] For the iron and steel (de Beer et al., 1998, Gielen and van Dril, 1997), for ammonia (Boot, 1994; de Beer and Blok, 1999), for ethylene (Gielen et al., 1996; de Beer and Blok, 1999), for electricity (SEP, 1996).

Table 6
Assumptions for the dynamic approach to benchmarking up to 2012[a]. Shown are the expected physical production growth and autonomous energy efficiency developments, either as annual improvement rates or as the expected value of the energy efficiency indicator in 2012, in the Netherlands and abroad (for the currently most efficient region and a potential new "most efficient region"). Also shown are the estimated energy savings and avoided CO_2 emissions compared to the autonomous development and a frozen efficiency development (de Beer and Blok, 1999).

Sector	Development of production	Autonomous energy efficiency development	Energy savings (PJ) compared to		CO_2 emission reduction compared to autonomous efficiency improvement (Mt)
			The frozen efficiency level	Autonomous efficiency improvement	
Iron and steel					
Hoogovens	From 6.2 to 7 Mt	0.2–0.5%/yr			
Nedstaal	No change	0	5–12	0	0
Currently most efficient region abroad[b]		0.2–0.5%/yr			
Ammonia					
Domestic	Stabilisation	0.2–0.5%/yr	14–27	10–22	0.3–1.1
Currently most efficient region abroad		0.1–0.3%/yr[d]			
New most efficient region abroad[c]		SEC→ 26–27 GJ/t			
Ethylene					
Domestic	1%/yr capacity expansion	0.5%/yr	22–26	17–21	1.3–1.6
Currently most efficient region abroad	0.5 Mt new capacity	0.5%/yr			
New most efficient region abroad	3%/yr capacity expansion	EEI→95			
Electricity gas	1.7–1.8%/yr				
Domestic[e]		$\eta \rightarrow$ 49–55%[f]			
Currently most efficient region abroad		$\eta \rightarrow$ 53–55%	41–64	−4[g]–+50	−0.6[g]–+2.8
New most efficient region abroad[h]		$\eta \rightarrow$ 54–57%			
Coal					
Domestic[e]		$\eta \rightarrow$ 39%	31–37	30–37	2.9–3.6
Currently most efficient region abroad		$\eta \rightarrow$ 41–42%			
Total			113–167	48–130	4–9 (rounded)

[a] Preliminary estimates for aluminium and chlorine are given by (de Beer and Blok, 1999): estimated energy savings are estimated to be 0.2–1.5 PJ for alminium and 1.9–2.1 PJ for chlorine compared to BaU. Avoided CO_2 emissions are expected to amount to 0.02–0.4 Mt for aluminium and 0.1–0.2 Mt for chlorine compared to BaU.

[b] No new "most efficient region" is expected to emerge because the average efficiency is not expected to be higher than that of Hoogovens (currently the 'best plant' for primary steel production).

[c] No new capacity is planned in OECD countries, only in developing countries (WEC, 1995). A new "most efficient region" is expected to emerge with an average SEC equal to the expected best plant SEC for the coming decade (de Beer and Blok, 1999).

[d] Improvement rate is expected to be lower for Canada because currently energy efficiency is better than that of the Netherlands.

[e] No new coal capacity, 15% of electricity demand is met through import and 20% is met through autoproducers (SEP, 1996).

[f] The upper limit of the range represents the case in which plants at the end of their lifetime are closed down according to the current shut-down schedule and replaced by new capacity. The lower limit represents the case in which these plants are kept in operation 10 additional years, before they are shut down and replaced.

[g] A negative number indicates an increase in energy consumption or emissions when production growth outweighs energy efficiency improvement.

[h] Gas-based only, since no substantial amounts of new coal-based capacity is expected to be installed except for India and China.

5–15% of the BaU energy consumption of the sectors analysed. The avoided CO_2 emissions resulting from the dynamic benchmark are estimated at 4–9 Mt in 2012. The range in the estimates indicates the different assumptions on the autonomous energy efficiency improvement rate and on whether or not a new 'most efficient region' is expected to emerge.

7. Expected results of policy alternatives

To put the calculated energy savings into context we compare them to the energy savings that would result from a continuation of the Long-Term Agreements that expired in 2000. The Benchmarking agreement has been introduced as an alternative to these Long-Term Agreements, which have a target that corresponds to an average annual efficiency improvement rate of 2%/yr[10]. The 2%/yr reduction of the energy efficiency index results in an EEI in 2012 slightly below 100 for the sectors listed in Table 6. However, the specific energy consumption of the best plants observed will also decrease in the 17-yr timeframe. The continued 2%/yr target results in an energy saving of 50–68 PJ in 2012 compared to autonomous efficiency developments of 0.2–0.5%/yr for the ammonia industry, the ethylene industry and the steel industry combined. Our preliminary estimate is that the Benchmark agreement (excluding electricity production) may result in half to two-third of that amount: 27–43 PJ.

We can also compare the results of the Benchmark agreement to the technical potential for energy-efficiency improvement. According to de Beer et al. (1998), the technical potential for energy savings in the chemical industry and the metal industry between 1995 and 2010 is 23–24% compared to frozen efficiency in 2010. This would translate in energy savings of about 80 PJ for the iron and steel industry, the ammonia industry and the petrochemical industry combined. This means that both the Benchmarking agreement and the alternative continuation of the Long-Term Agreements will remain well within the limits set by the technical potential.

8. Discussion

A number of issues, which may influence our results, are discussed here.

Most of the data used in this analysis have been gathered in the INEDIS database by the INEDIS network. Within INEDIS these data are checked with the assistance of national experts for structural errors and consistency, such as system boundaries, conversion factors used (e.g. LHV or HHV), etc. In general, our methodologies turn out to have an accuracy of $\pm 5\%$ (Farla and Blok, 2001) if incidental errors are avoided. By using time-series data and by cross-checking with national sources, as we have done, at least some of the incidental errors are avoided.

An error of 5% in the SEC results in an error of also 5% in the EEI. The sectoral reference SEC, however, is aggregated out of several individual product or process SECs. It is not very likely that all the individual SECs have the same error (i.e. also in the same direction). Furthermore, the deviation in reference SEC has in principle a similar influence on all countries. Therefore, we expect the deviation in EEI to be $<5\%$. The uncertainty in the estimated energy savings in the static benchmark can then be calculated to be 43–49 $\pm$ 19 PJ. It must be noted that the largest part of this uncertainty originates from the results for ammonia and ethylene production. However, for these sectors data have been collected directly from industry. Also, both energy consumption data and production data are from the same source. We, therefore, expect the error in these sectors to be smaller than 5%. The estimated error can, therefore, be considered as an upper limit to the uncertainties.

The efficiency of electricity generating plants is influenced by ambient temperature and the cooling medium used. A higher ambient temperature leads to a slightly lower efficiency (0.1–0.2%/°C (Phylipsen et al., 1998a)). Surface water cooling leads to slightly higher efficiencies than when cooling towers are used. For coal-based electricity generation this will not influence the results, since Denmark and the Netherlands have a comparable climate (based on the number of degree-days for both countries the average temperature in Denmark is calculated to be <1°C lower than the average temperature in the Netherlands). The availability of surface water is also comparable in both countries. For gas-based electricity our estimated results may be slightly affected. The average temperature in Turkey is 2–10°C higher than in the Netherlands, depending on the region. The average difference with the Netherlands is estimated at 6°C. The lower humidity in Turkey, compared to the Netherlands, moderates the negative effect the higher temperature has on the generating efficiency in Turkey. The overall effect is expected to be about 1%, increasing the total effect of the Benchmarking agreement by approx. 5 PJ.

No disaggregate data were available on the energy efficiency of refineries. According to Solomon (as cited in (EZ, 1997)) the average energy efficiency index in the Netherlands is lower than the average indices for Europe, North America and the Pacific region. Based on the data available from the LTA process Novem estimates that benchmarking would lead to energy savings 8.2 PJ and 0.6 Mt CO_2, in case the benchmark is set at the best 25% (de Beer and Blok, 1999). Data for more stringent benchmarks are not available. In analogy to the results for ethylene and ammonia we expect a Top 10% benchmark to result in an amount that is roughly one-third higher than that amount (i.e. about 11 PJ energy savings and 0.8 Mt avoided CO_2 emissions).

The analyses are based on average efficiencies per sector rather than efficiencies of individual plants. Plants that are more efficient than the benchmark will not have to save energy, while plants below the

[10] An average efficiency improvement rate of 2%/yr corresponds to the target of 20% efficiency improvement (reduction in average specific energy consumption) between 1989 and 2000 (EZ, 1997). We have calculated energy savings by assuming the energy efficiency index decreases with 2%/yr (excluding feedstock energy consumption). For steel we have assumed a 1%/yr decrease, because in the current long-term agreements only half of total energy consumption is covered by the agreement.

benchmark efficiency will have to save more energy than the average. This means that, while the average saving that we calculate is zero, there may be savings in case each individual plant has to satisfy the benchmark criteria. The overall effect will depend on the differences in efficiency between individual plants in the Netherlands and the relative size of the plants. Possible differences between the average efficiency-based estimate and the individual plant-based estimate are furthermore reduced when a company-wide approach is chosen. The company-benchmark is basically an average efficiency-based approach. For the iron and steel industry and ethylene production the distinction between the two approaches is not relevant, because there are no individual plants that are more efficient than the benchmark. Only in the ammonia industry the estimated energy savings in the individual plant-based approach are higher (by 1 PJ) than in the collective approach. In the electricity-generating sector one gas-based plant is expected to be more efficient than the benchmark. The plant, however, is owned by a company that also owns a larger, less efficient plant. The average efficiency of the plants is roughly the same as the benchmark (capacity and efficiency data from (SEP, 1996)). It, therefore, seems likely that the company will opt for the company approach so that no additional efforts are required. In that case no difference in expected energy savings between the average efficiency-based approach and the company-based approach exist.

Overall, we do not expect that the use of individual plant-based efficiencies will have a major effect on the results.

9. Conclusions

The Dutch government has made a voluntary agreement with industry in which industrial companies are required to belong to the top-of-the-world in terms of energy efficiency. In this article an estimate is given of the effect of such an agreement on energy consumption and CO_2 emissions. Estimates were based on a static approach: they represent the amount of energy that would have been saved and CO_2 emissions that would have been avoided in the hypothetical case that the Dutch industry would currently be among the most efficient in the world. If the benchmark is set at the efficiency of the most efficient region in the world, energy savings are estimated to be about 45–50 PJ (or 5% of the current energy consumption of the sectors analysed). Avoided emissions are estimated to be nearly 4 Mt CO_2.

When developments in energy efficiency—both in the Netherlands and abroad—and the production volume are taken into account, the potential for energy efficiency improvement as a result of benchmarking would be 50–130 PJ in 2012 (5–15% compared to Business as Usual developments), or 4–9 Mt CO_2. Hence, in the best case a doubling of the potential results in 2012 compared to the static approach. In the worst case the potential is equal to the results of the static approach.

Our analysis suggests that the energy savings from a Benchmarking agreement will be smaller than what might be expected of a continuation of the Long-Term Agreements (i.e. a 2%/yr energy efficiency improvement). In both approaches, the results are substantially below the technical energy-saving potential.

Abbreviations and country codes

aggr.	aggregate
AU	Austria
AUS	Australia
B	Belgium
BaU	Business as Usual
CE	Central Europe (other Germany and Austria)
D	Germany
F	France
Hou	Houston area
I	Italy
IDN	Indonesia
IRL	Ireland
J	Japan
K	Korea
Lou	Louisiana
Med	Mediterranean
NF	Northern France
NL	the Netherlands
OTex	other Texas
Pers.Gulf	Persian Gulf region
Rhine	Rhine river area (in Germany)
S.Am	South America
S.Asia	South Asia
Scan	Scandinavia
UK	United Kingdom
US-NC	USA-North Central (includes Idaho, Illinois, Indiana, Iowa, Kansas, Michigan, Minnesota, Missouri, Nebraska, North Dakota, Ohio, South Dakota, Wisconsin)
US-SC	USA-South Central (includes Arkansas, Louisiana, Oklahoma, Texas)
US-SE	USA-South East (includes Alabama, Florida, Georgia, Kentucky, Mississippi, North Carolina, South Carolina, Tennessee, Virginia, West Virginia)

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